Observing and Modeling the Surface Scattering Layer of First-Year Arctic Sea Ice

Richard E. Moritz
Applied Physics Laboratory
University of Washington
Seattle, WA 98105-6698
Phone: 206.543.8023 Fax: 206.616.3142
email: dickm@apl.washington.edu

Bonnie Light
Applied Physics Laboratory
University of Washington
Seattle, WA 98105-6698
Phone: 206.543.9824 Fax: 206.616.3142
email: bonnie@apl.washington.edu

Award Number: N00014-03-1-0120

LONG-TERM GOALS

The long-term goal of this work is to increase the quantitative understanding of the partitioning of incident solar radiation by sea ice. The partitioning of shortwave radiation into components backscattered to the atmosphere, absorbed by the ice, and transmitted to the ocean is central to ice-albedo feedback, the mean annual cycle of ice thickness, mechanical properties of the ice, and the quality and quantity of light available to under-ice biological communities. This partitioning is known to depend strongly on the physical properties of the ice cover, including ice concentration, snow cover, depth and size of surface liquid water ponds, and the presence of surface scattering layers. The focus of this research is to address the impact of surface scattering layers on the partitioning of incident solar radiation at the atmosphere-sea ice-ocean interface.

OBJECTIVES

The overall objective of this work is to develop a conceptual model of how surface scattering layers on melting first-year sea ice govern the partitioning of incident shortwave radiation. This includes improving the physics employed in models that relate the physical and optical properties of sea ice.

To achieve this objective, we have conducted field observations and model simulations of scattering both within the surface layers and interior layers of sea ice. Observations focus on (i) the evolution of surface scattering layers, and (ii) how the physical properties of sea ice are related to their inherent optical properties (IOPs). Modeling efforts focus on diagnosing relationships between the structural and optical properties of these layers which are typically drained and have low density and coarse grains. Results will ultimately be used to improve parameterizations of the surface energy and mass balances of sea ice during summer and will treat both bare and ponded ice.

Specific objectives include: (i) design and implement field equipment for measuring the spectral radiance transmitted through core samples of sea-ice; (ii) acquire measurements of spectral transmission through sea-ice during the onset and duration of the melt season, including drained and flooded bare ice, drained and flooded ponded ice, together with measurements of the physical properties (temperature, salinity and density) of each sample; (iii) calibrate the field measurements of spectral transmission to determine IOPs by combining optical modeling and laboratory calibration measurements; (iv) analyze and interpret the relationships between IOPs and physical properties to establish the conceptual model.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2006**	2. REPORT TYPE	3. DATES COVERED **00-00-2006 to 00-00-2006**
4. TITLE AND SUBTITLE **Observing and Modeling the Surface Scattering Layer of First-Year Arctic Sea Ice**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Washington,Applied Physics Laboratory,1013 N.E. 40th St.,Seattle,WA,98105**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

APPROACH

Observations of the structural and optical properties of first-year summer sea ice were made simultaneously in the field. A radiative transfer model is being used to interpret the optical observations; a "structural-optical" model is being developed to predict inherent optical properties (IOPs) from structural properties. IOPs include those optical properties which are fundamental to the ice. They include scattering and absorption coefficients and scattering phase functions, and are generally not directly observable in multiply scattering media. All radiative transfer models require knowledge of these IOPs, along with information about the domain geometry and incident light, to predict "apparent optical properties" (AOPs). AOPs are observable quantities, including the albedo, transmittance, and total absorption. Inferred and predicted IOPs are compared so that the structural-optical model can be improved and tested. A useful quantity known as the "similarity parameter" (s) is also being employed. In this application, we take s to be the magnitude of the scattering coefficient (σ) multiplied by (1- g), where g is the scattering asymmetry parameter. Use of this parameter as a bulk measure of the IOPs related to scattering facilitates the analysis of the data. The process of integrating physical and optical data from the upper portions of the ice will lead to our objective: a quantitative understanding of the role of the surface scattering layer in the optical properties of a summer ice cover.

Our effort during the final year of this project has focused on calibrating the optical core jacket, cataloging and analyzing the optical and physical data collected during the 2005 field experiment, and initial analysis and interpretation of the data.

The optical core jacket consists of a specialized core barrel coupled with optical sensors for measuring the amount of light transmitted through an ice core sample. Measurements made with the core jacket use a bootstrap approach. Once a core was removed from the ice, it was placed within the jacket. Coupled optical detectors were used to measure T_λ for ambient diffuse incident radiation through the core. The top section of the segmented barrel was then removed (approximately 1 – 2 cm), the ice carefully sawed off, and another T_λ measurement made. This procedure of removing segments of the ice core and making sequential T_λ measurements has yielded a data set detailing the vertical structure of transmitted spectral radiance within the surface scattering layers and throughout the core. From these direct measurements of raw (or "jacket") spectral transmittance (T_λ) we estimate the IOPs using a two-dimensional Monte Carlo Radiative Transfer Model ("2DMCRT"; *Light et al.*, 2003) to correct for the effects of the jacket's optical properties and finite geometry. After comparing T_λ with a look-up-table (LUT) of 2DMCRT simulations, a vertical profile of s within the sample is inferred.

WORK COMPLETED

During the past year, calibration of the optical core jacket and analysis of the field data have been carried out.

Calibration of the optical core jacket is necessary so that the correct properties can be supplied to the 2DMCRT. Some elements of the calibration have been carried out in the laboratory and some in the field. In particular, 4 features need to be calibrated: (i) the effective field-of-view of the fiber optic cables that were used to couple the jacket to the spectrophotometer, (ii) the absorbing properties of the acrylic floor used in the jacket to support the core sample, (iii) the scattering properties of the opal glass diffuser plate used on top of the jacket, and (iv) the optical response of the jacket cylinder itself. Experiments were carried out in the laboratory to estimate (i), (ii), and (iii). Part (iv) was calibrated in

the field where measurements of T_λ were made for three dilutions of latex calibration spheres (Duke Scientific). Observed values of T_λ for the three concentrations of spheres were compared with a LUT of 2DMCRT model predicted T_λ values using scattering parameters for the spheres derived from Mie theory. While each segment of the calibration has been carried out, there remains some uncertainty about the most appropriate effective field-of-view for the fiber optic cables used in the field experiment. These uncertainties do have significant effect on the inferred IOPs, as will be discussed in the Results section below.

Analysis of observations made on first-year sea ice in the Chuckchi Sea off of Barrow, Alaska is ongoing. Field measurements were made between 17 May and 23 June 2005. This interval extended from the beginning of the melt season until access to the ice became impractical. Ice cores were sampled and optical measurements made on 31 different days. By making measurements in the jacket quickly at the coring site, the amount of brine drainage from samples prior to the measurement was minimized. The sampling included time series of specific ice types: snow covered ice, ice cleared of snow, bare melting ice, and ponded ice. We also carried out studies to assess the repeatability and the spatial variability of the measurements.

Data collection procedures were as follows. First, a measurement of spectral albedo was taken at each study site prior to trampling or coring. Spectral albedo data are particularly useful for analyzing the core jacket data in the uppermost sections of the ice. Two coring locations were typically identified. Early in the season, snow covered and snow free cores were obtained, later in the season, bare and ponded ice cores were obtained. Initially, the uppermost 15 to 35 cm of each core was placed in the jacket. This permitted the surface layers to be sliced off with the highest vertical spatial resolution practical. This approach has yielded a highly resolved vertical profile of the IOPs within the uppermost 15 – 35 cm of the ice. Subsequently, 13 cm thick sections were measured from interior portions of the core sample.

The base of the core jacket was constructed to be watertight, permitting the sample to be flooded with either pond water or sea water, as appropriate. Typically the water drained immediately from those cores extracted from ponds. Measurements were made on both the drained and re-flooded sample. Cores extracted from below-freeboard bare ice tended to drain more slowly, but this arrangement made it possible to re-flood those samples as well. The flooded samples represent our best approximation to “in-situ” conditions.

RESULTS

We present results from a study site (21 June) whose characterization of both bare and ponded ice represents the processes being studied during this project, along with time series data that span the entire experiment.

21 June study site- On this day, cores from both bare and ponded ice types where measured in the optical core jacket. Figure 1 shows photographs of the two measurement sites, the bare ice core, an example of T_λ data from the core jacket, and vertical profiles of the similarity parameter inferred from the T_λ data and the 2DMCRT model.

The pond depth was 10 cm at this location. The bare ice freeboard was 14 cm. The photograph of the bare ice core is annotated to show approximate extent of the surface scattering layer (SSL), drained

layer (DL), and interior ice. The T_λ curve was taken from the core jacket measurement of the 3 – 19 cm deep core section (bottom of sample is at break shown in photograph). This includes the intact portion of the SSL and much of the DL. This spectrum, and nine additional ones for this core, were used to construct the *s* profile shown in (d). Similar spectra for the ponded ice were used to infer the ponded *s* profile as well.

The values of *s* that have been inferred are sensitive to the calibration of the fiber optic field-of-view. As mentioned, there remains some uncertainty in this calibration. For this reason, the magnitudes of *s* presented in Figures 2 and 3 are provisional. Comparisons between *s* values are relative. The *s* profiles indicate that the optical properties of the interior bare and ponded ice at this date are indistinguishable. A recent study of optical profiler data measured during the SHEBA project (*Light et al.,* submitted*)* showed that total scattering within interior bare and ponded ice was approximately the same, as well as being independent of time during the summer melt season. The profile for bare ice also indicates that *s* increases by a factor of 40 between the interior and the SSL. This result is also corroborated in the same recently submitted manuscript. This large gradient in *s* is commensurate with the large changes in density over the depth of the ice measured at this site (see Figure 2).

Figure 2 shows ice density profiles for a selection of sites during the experiment. The measured density generally shows strong decreases near the surface in the SSL and DL. These decreases are accentuated with time. The ponded ice (23 June) shows very small density, but because the ice there is beneath the reservoir of pond water, it is perpetually flooded and the scattering is not as large as that found in the SSL of bare ice. Because both the scattering coefficient and the asymmetry parameter respond to changes in the size and number of brine and gas inclusions in the ice, we expect the *s* profile to be inversely correlated with the density profile. Where the ice density is large (interior ice) the inclusions are primarily filled with brine (high *g* value) and the value of *s* is small; where the density is small (SSL and DL), the inclusions are enlarged and draining (increased scattering coefficients, decreasing *g* values) and the value of *s* is large.

Time dependence- Figure 3 shows inferred *s* values for all 13 cm thick flooded sections placed in the core jacket over the course of the experiment. The left panel shows bare ice, the right panel is for ponded ice. Similarity parameters for interior ice (everything below 50 cm depth; black and red symbols) are small, indistinguishable between bare and ponded surfaces, and appear to be independent of time. Values of *s* from samples that begin to sample the DL (30 – 50 cm; green symbols) have larger magnitude. Values inferred for the DL (20 – 30 cm; blue symbols) show magnitudes significantly elevated above the values for interior ice. Values inferred for the SSL (0 – 20 cm; cyan symbols) show very large magnitudes and appear to increase with time. This is likely the most significant time dependent change seen in the inferred optical properties.

Three broad concepts are emerging from this work: (i) a 3-layer structure for specifying the vertical variation of optical properties of both bare and ponded sea ice, (ii) the optical properties found in the ice interior are independent of time, and (iii) a picture of the evolution of scattering near the surface of bare and ponded ice as the melt season progresses. A generalized 3-layer structure for specifying the vertical variation of optical properties includes identification of the SSL, DL, and interior ice. For bare ice, the SSL is generally the uppermost 5 -10 cm of the ice. The interior is everything below freeboard. The DL occupies the space between. This 3-layer structure facilitates modeling radiative transfer in sea ice within large scale models. Clearly, differences in the transmittance of solar radiation to the ocean beneath bare and ponded ice derive from the presence or absence of a SSL and DL and the total ice

thickness. This study found that scattering in the interior of the ice did not change with time. Comparisons with other studies looking at the optical properties of interior ice (*Light et al*., submitted) show similar behavior. We are also developing a picture of how the optical properties of an ice cover progress as the surface undergoes the transition from bare to ponded. The albedo of the ice drops precipitously as a thin pond forms. This drop in albedo requires additional shortwave energy to be absorbed within the surface layers of the ponded ice, which in turn, drives increases in scattering.

TRANSITIONS

We anticipate that results of this study will be incorporated into a revised parameterization of sea ice thermodynamics and this parameterization will then be incorporated into climate models (such as the Community Climate System Model, CCSM) and operational models (such as PIPS). Furthermore, these results will facilitate the development of sampling strategies for the collection of more realistic spectral transmittance data under horizontally inhomogeneous ice covers.

RELATED PROJECTS

This work is relevant to a recently completed project, “A new shortwave radiation parameterization for the CCSM sea ice model” (NSF ATM-0454311). Additionally, it is relevant to two ongoing projects, “Collaborative Research on observing the morphological and optical characteristics of the summer Arctic ice cover during the 2005 Trans-Arctic Expedition” (NSF ARC-0454900) where the optical core jacket is currently being deployed in the laboratory on ice cores sampled during the cruise, and “Collaborative research on sunlight and the arctic atmosphere-ice-ocean system” (NSF ARC-0531026) where estimates of the amount of solar radiation penetrating the ice cover are being explored on a basin-wide scale.

REFERENCES

Light, B., T. C. Grenfell, and D. K. Perovich, Transmission and absorption of solar radiation by arctic sea ice during the melt season, submitted to *J. Geophys. Res.,* October 2006.

Light, B., G.A. Maykut, and T.C. Grenfell, A two-dimensional Monte Carlo model of radiative transfer in sea ice, *J. Geophys. Res., 108*(C7), 3219, doi:10.1029/2002JC001513, 2003.

PUBLICATIONS

Light, B., T. C. Grenfell, and D. K. Perovich, Transmission and absorption of solar radiation by arctic sea ice during the melt season, submitted to *J. Geophys. Res.,* October 2006.

Briegleb, B. P. and B. Light, 2006: A Delta-Eddington Multiple Scattering Parameterization for Solar Radiation in the Sea Ice Component of the Community Climate System Model, NCAR/TN-472+STR, 100pp.

Huck, P.E., B. Light, H. Eicken, M. Haller, Mapping sediment-laden sea ice in the Arctic using AVHRR remote-sensing data: Atmospheric correction and determination of reflectances as a function of ice type and sediment load, submitted to *Remote Sensing of Environment,* August 2006.

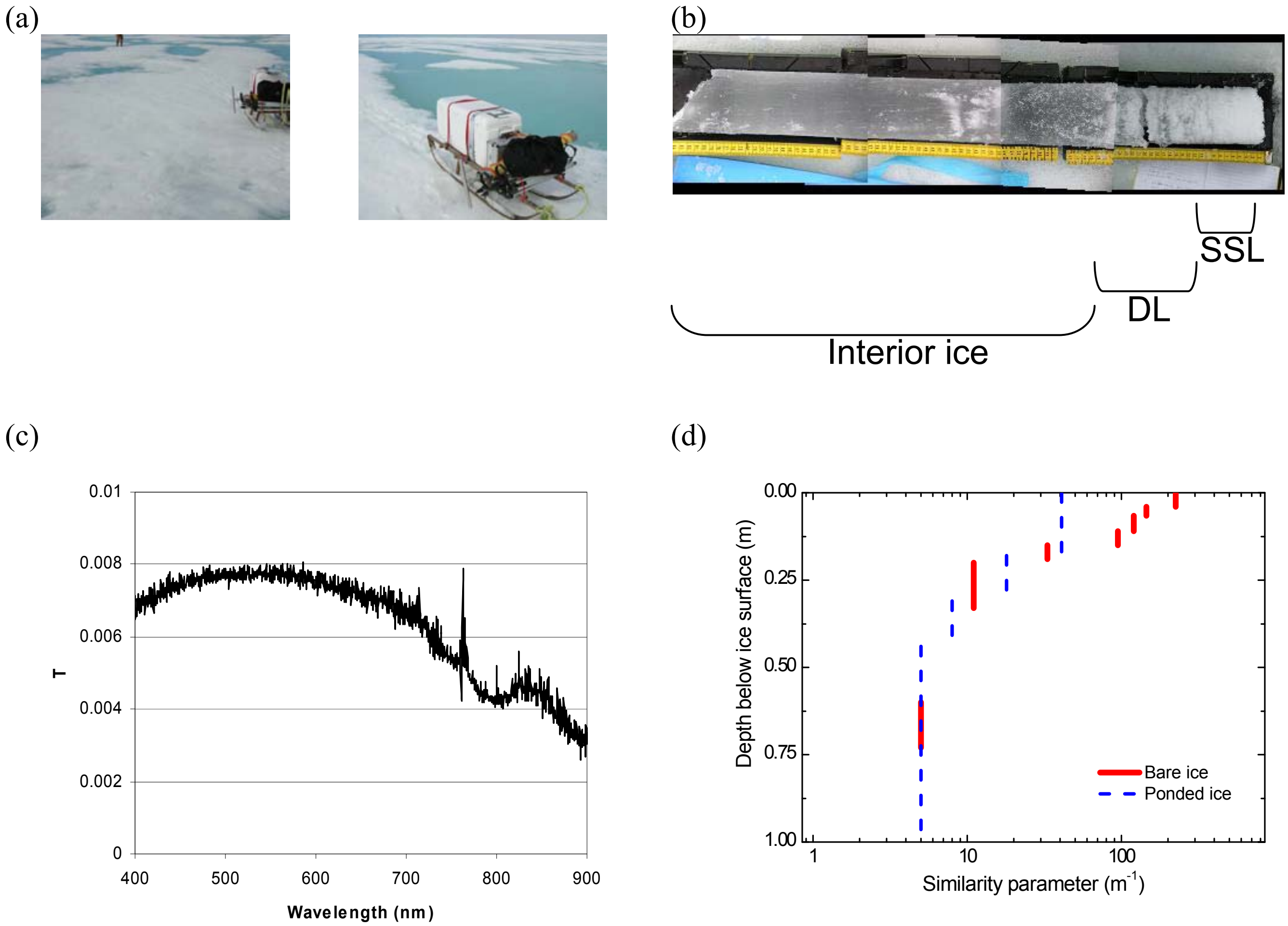

Figure 1. Study site on 21 June 2005. (a) photograph of bare, melting first-year ice site and adjacent ponded ice site, (b) photomosaic of a core sample extracted from the bare ice site, (c) sample T_λ for the 3 – 19 cm section, and (d) vertical profiles of scattering coefficient inferred from the optical core jacket measurements at both bare and ponded sites.

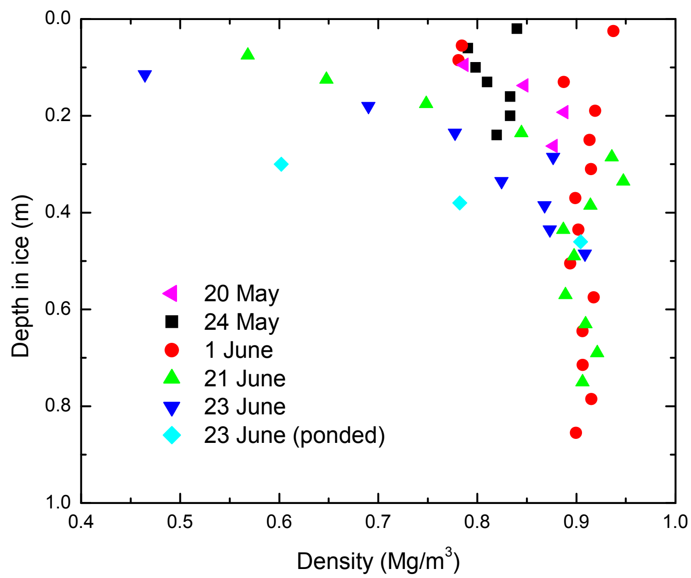

Figure 2. Ice density profiles for bare ice sites on 20 May, 24 May, 1 June, 21 June, and 23 June (bare and ponded). Profiles show decreases in surface density increasing as time progresses.

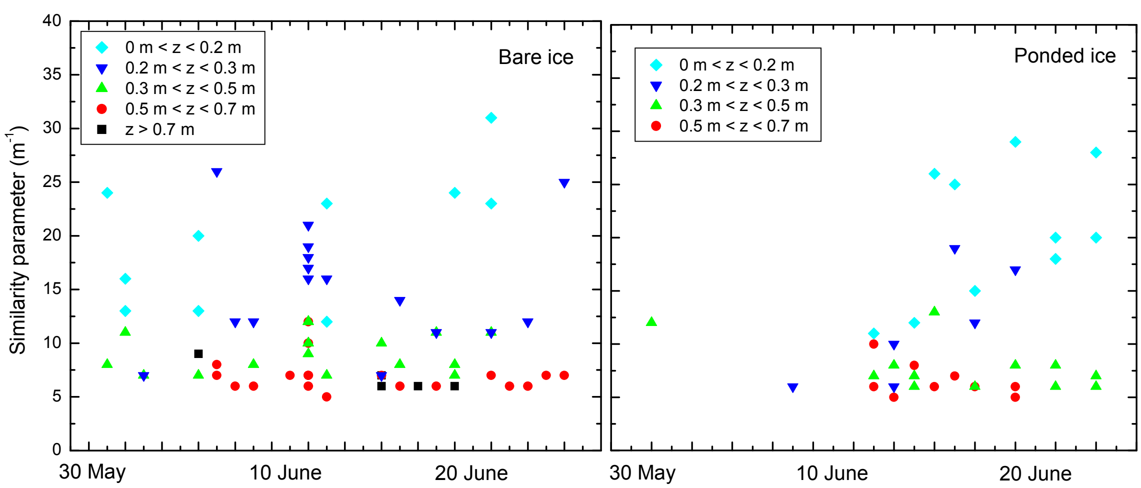

Figure 3. Time series of inferred scattering coefficients for 13 cm thick flooded samples throughout the depth of the ice.